Application of Boundary Layer for Modeling of Solitary Wave Runup

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論文内容要旨

The purpose of this study is to apply boundary layer in wave run up simulation. The importance of boundary layer approach to assess bed stress under wave motion is very crucial. Especially in bed stress related analyses, i.e. sediment transport and scouring. They are highly importance in relevance to coastal morphology changes due tot tsunami wave.

Shallow water equation (SWE) model has been widely used for wave run up simulation, particularly long wave, due to its shared properties with shallow water wave. SWE model is known as an efficient model, with relatively accurate results. The model is flexible. It easily adapts wet/dry treatments. Nevertheless, SWE model frequently uses Manning method for approaching bed stress, which is unsuitable for bed stress assessment under wave motion. The Manning method estimates bed stress at the same direction with free stream velocity and in linear relation to the square of velocity divided by depth. Thus, there can be no sign change and phase difference between free stream velocity and bed stress. Therefore, it can not accurately simulate unsteady flow, such as wave motion. It is commonly known that phase difference between free stream velocity and bed stress is one of the important parameters to estimate bed stress under wave motion. Boundary layer approach will provide a more accurate estimation of bed stress under wave motion.

The k-ω model has shown it benefits for assessing boundary layer properties, including bed stress estimation. The model has shown its ability to reproduce known bed stress behaviors under unsteady flow such as the sign change and phase difference. The model has shown its good performance in assessing bed stress and vertical velocity distribution under oscillatory wave experiments from previous study. Although some of empirical formulas have started to incorporate the phase difference, still, they are outperformed by direct assessment of bed stress from boundary layer using the model.

The study is emphasized on the long wave run up simulation, in relevance to tsunami wave study. A new method for wave run up simulation was developed by coupling SWE with k-ω model. SWE and k-ω model are coupled to get the benefits from both, the efficiency of SWE and direct assessment of bed stress from boundary layer using k-ω. The basic idea for the development relies on the implementation of bed stress from the boundary layer to the momentum term. The Manning method approach in assessing bed stress is replaced with boundary layer approach.

Calculation begins with an initial condition of the parameters. Initial value of friction coefficient is stated for bed stress calculation in SWE model. The velocity obtained from the SWE model is applied as the free stream velocity boundary condition in the k-ω model as given bellow.

$$U \rightarrow -\frac{\partial P}{\partial x} = \frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x}$$

with U is the obtained free steam velocity from SWE, and P is the pressure applied in the boundary layer. x corresponds to horizontal distance and t is the time. Furthermore, the bed stress obtained from the k-ω model is applied in the momentum equation of SWE model.

$$\frac{\tau_0}{\rho} = (\nu + \nu_t)\frac{du}{dy} \rightarrow \frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\frac{\partial(h+z_b)}{\partial x} + \frac{\tau_o}{\rho h} = 0$$

Here, τ_o is bed stress, ρ is the fluid density, ν is the fluid viscousity, ν_t is the eddie viscousity based on the turbulence closure from k-ω, g is gravity, u is the velocity in the boundary layer, y is the vertical distance. h and z_b are the water depth and bed elevation respectively. The process continues until the end of simulation time. The developed method, which is called SCM (Simultaneous Coupling Method) was verified and applied to canonical problems, non-breaking and breaking solitary wave run up on a sloping beach. The SCM employs shock capturing scheme to handle shock due to wave breaking.

Each model was verified separately with appropriate cases. The k-ω model was verified by assessing the boundary layer properties (vertical velocity distribution and bed stress) under random wave, oscillatory wave and analytical approach. Furthermore, the application of k-ω model in SCM for wave run up is further verified by bed stress and turbulent intensity comparison to experiment. The SWE model along with SCM was verified with solitary wave run up on a sloping beach (canonical problems). SCM was used to assess and analyze various properties of boundary layer, especially in bed stress assessment. Moreover, momentum balance analysis was conducted to assess bed stress significant area. k value and evolution were also investigated.

In both cases, non breaking and breaking wave, run up height comparison shows that the SCM provides a better water profile comparison to the canonical problems data set as well as better agreement of run up height with the run up law. One of the disadvantages of Manning method is the requirement to obtain the relative Manning value based on the flow regime. This is clearly shown in the non-breaking wave case (laminar regime) where the Manning value has to be emphasized to obtain a good results. The Manning value in the breaking wave case was found to be similar with the reference. Breaking wave mechanism in the model is assessed showing that the adopted shock capturing sacheme actively dissipates the wave in breaking area, noted with ratio of wave height and depth of approximately 0.8.

Investigation of bed stress reveals that the SCM successfully reproduced the phase difference and the sign change behavior exactly where the Manning method fails. In addition, the Manning method tends to give a higher bed stress magnitude in shallower area, and lower bed stress in deeper area, compares to the SCM. This may be the effect of the flow regime since the Re will be magnified as the wave approaches the shoreline. Further assessment of bed stress reveals that the bed stress leaving the shoreline has more significant effect than bed stress moving towards the shoreline. However, slight difference was observed in comparison between the non-breaking and breaking wave case. For the non-breaking wave case, the location of extreme values for bed stress, leaving and moving toward the shoreline, is situated near the shoreline. In the breaking wave case, the location of bed stress extreme value with the direction leaving the shoreline is shifted to the shallow area, although the extreme value with the direction moving toward the shoreline is still situated around the shoreline. This is due to the hydraulic jump-like behavior during the run down process, which is strong enough to produce reflected wave. This does not occur in the non-breaking wave simulation.

Momentum balance analyses in non breaking wave simulation provides temporal and spatial information of bed stress significant area. The overall run up and run down process can be classified into five phases. Phase I is the propagation process in deep area. During this process, the bed stress will have no significant effect on the flow. The momentum is mainly governed by the local acceleration and pressure gradient. Phase II occurs when the wave approaches the shoreline, causing small rundown at the wave front. The small rundown does not have the same behavior with the propagation process although the main wave still propagates as in phase I. The momentum balance in the small rundown is governed mainly by pressure gradient term and bed stress term. Phase III occurs as the run up process occurs with significant effect from bed stress. At this time, the main wave has reached the shoreline. Phase IV occurs around the maximum run up process and at the initial stage of run down. At this phase the process behaves as in Phase I. Phase V occurs as run down process starts in which momentum balance is mainly governed by bed stress and pressure gradient.

Some differences were observed in the momentum balance between non-breaking wave and breaking wave. In the later, the effect of convective acceleration is greatly magnified, especially during the breaking wave and in run down. The overall analyses lead to the same tendency as in non-breaking wave. Phase I does not clearly shown in the breaking wave case. The effect of the propagating wave to shoreline appears rapidly, marking the start of phase II almost instantaneously. Phase III occurs during the run up. It is noted that the breaking wave occurs in phase III. Momentum balance rapidly changes condition around maximum run up, hence, phase IV was not observed. Phase V immediately starts after phase III. The run down motion in breaking wave case does not always in line with the main body of the wave. It is observed that although the main wave runs up the shore, some part of the wave has started to run down. Thus, when the run down process starts after maximum run up height reach, the first run down has already reach shoreline. Bed stress is significant in both run down motions.

Empirical parameter is introduced to classify these phases. Based on the numerical experiments, the ratio of non-dimensional velocity to water wave height seems to corresponds to these phases. The ratio value of 40 provides classification of run up and run down phases for the non breaking wave simulation. In the breaking wave simulation, the ratio value of 10 provides classification of run up and run down phases for the breaking wave. The value difference is caused by wave breaking process.

There is no significant turbulence in the non-breaking wave simulation. However, in the breaking wave simulation, k value generates higher as the wave approaches the shoreline. k value is higher during run up than run down. It is noted that k value is generated from bottom and increases as it gets closer to shoreline. Furthermore, the near bed k value near the shoreline showed significant different profile especially in the slow deceleration phase due to the wave deformation. Comparison with experimental data verifies the turbulent condition was achieved in the breaking wave case around the shoreline. It is found that the k value corresponds to the bed stress fluctuation. The fluctuation increases along with the increase of k value. Moreover, spatial Reynolds number shows that significant increase in its magnitude starts to occur after the breaking point.

Overall, SCM had been verified and used to conduct various analyses under solitary wave run up. SCM is efficient and flexible, yet able to provide various information regarding boundary layer under wave. The Manning method may provide reliable result, however, it does not reflect the physical condition of the wave run up process. Moreover, the choosing of Manning value should be carefully assessed prior to simulation. It is recommended to replace the common Manning method with boundary layer approach for wave run up modeling. Boundary layer approach accurately describes the process and mechaniscm of bed stress generation under wave rup. SCM is one of the possibility to incorporate boundary layer approach for wave run up simulation. Further enhancement of the model may covers verification of SCM for rough bed. Investagtion should be conducted regarding the use of the proposed parameter of bed stress significant to reduce simulation time.

論文審査結果の要旨

孤立波は津波を近似する波動として多用され，孤立波の遡上に関する数値計算・水理実験がなされている．数値モデルにおいてはマニングの粗度係数を援用することが多いが，波動は基本的に非定常運動であり，定常流抵抗則の適用は厳密な取り扱いとは言えない．本論文では孤立波遡上現象に対して底面境界層モデルを適用し，非砕波・砕波時の遡上現象を予測するモデルを開発した．さらに，定常量抵抗則を援用した時の精度についても検討を行った．

第１章では，「序論」として本論文の目的と構成について述べている．

第２章においては，平坦床および斜面上における孤立波に関する既往の研究を紹介し，これまでの扱いの問題点を明らかにしている．

第３章においては，浅水流方程式と乱流モデルｋ－ωモデルを組み合わせたモデル（Simultaneous Coupling Method, SCM）を提案している．また，砕波の数値計算手法についても，既存の衝撃捕捉法による取り扱い方法を提案した．浅水流モデルにおいて底面境界層の扱い高度化したモデルとして位置づけられ，きわめて重要な成果である．

第４章においては，実験データの蓄積がある水平上の周期波を対象としてSCMの検証を行い，十分な精度を有することを示している．これは，流体力学上，有益な知見である．

第５章においては，斜面上を遡上する非砕波孤立波を対象とする数値計算を行い，波形・遡上高さについて既往の実験を良好に再現することを示した．また，基礎方程式の各項の大きさを評価し，底面せん断力項を加味すべき沖側境界に関する経験式を提案した．これは，数値計算負荷の低減につながる知見であり，重要な成果である．

第６章では，斜面上を遡上する砕波孤立波を対象とする数値計算を行い，波形・遡上高さ・底面せん断力・乱れ強さ・乱流遷移過程について既往の実験結果を良好に再現することを示した．これまで，浅水流モデルにより乱流特性まで取り扱うモデルは皆無であり，きわめて重要な成果である．

第７章は総括及び今後の課題を述べたものである．

以上要するに，砕波・非砕波のケースについて孤立波遡上を精度よく推定するモデルを提案しており，今後，津波による土砂移動モデルの高精度化など多岐にわたる応用の可能性を有している．したがって，海岸・海洋工学分野の発展に寄与するところが少なくない．

よって，本論文は博士(工学)の学位論文として合格と認める．